



Development of a Canopy Atmospheric Modeling System for use in Simulating Smoke Dispersion from Low-Intensity Fires

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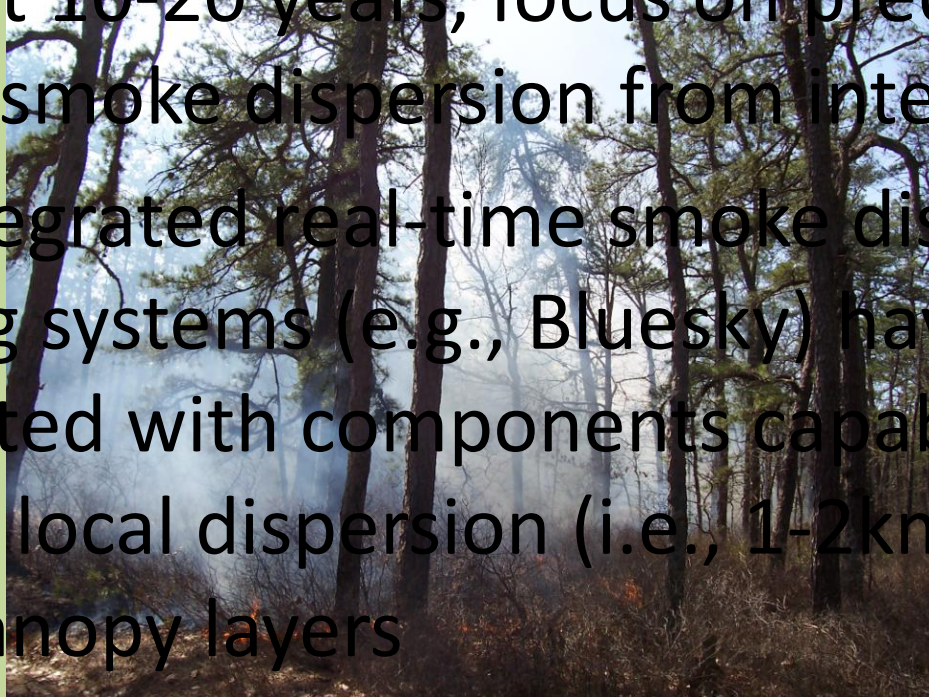
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Motivation

- Smoke dispersion from wildland fires is a critical health and safety issue
- Over past 10-20 years, focus on prediction has been on smoke dispersion from intense fires
- Most integrated real-time smoke dispersion modeling systems (e.g., Bluesky) have not been tested with components capable of handling local dispersion (i.e., 1-2km away) within canopy layers



Modeling of Smoke Dispersion from Low-Intensity Fires

- Particularly challenging due to the effect on dispersion of critical factors such as
 - near-surface meteorological conditions
 - local topography
 - vegetation
 - atmospheric turbulence within and above vegetation layers
- Important: Exchange of particles through vegetation canopy

Overall Modeling Strategy

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- The figure consists of two parts. On the left is a map of the Pine Barrens region, showing various counties including Burlington, Camden, Gloucester, Cumberland, and Atlantic. Key locations marked include Silas Little, Fort Dix, Brendan Byrne, Coyle Field, Cedar Bridge, Batsto, Warren Grove, and Pamona. A legend indicates 'Tower Sites' and 'NFP Project'. On the right is an aerial photograph of a dense forest landscape with a small body of water in the distance.
- Laboratory (PNNL) Integrated Lagrangian Transport (PILT) Model
- Evaluate performance of models with existing datasets & recent burn data
 - e.g. Silas Little Experimental Forest: 20 Mar 2011



Overall Modeling Strategy

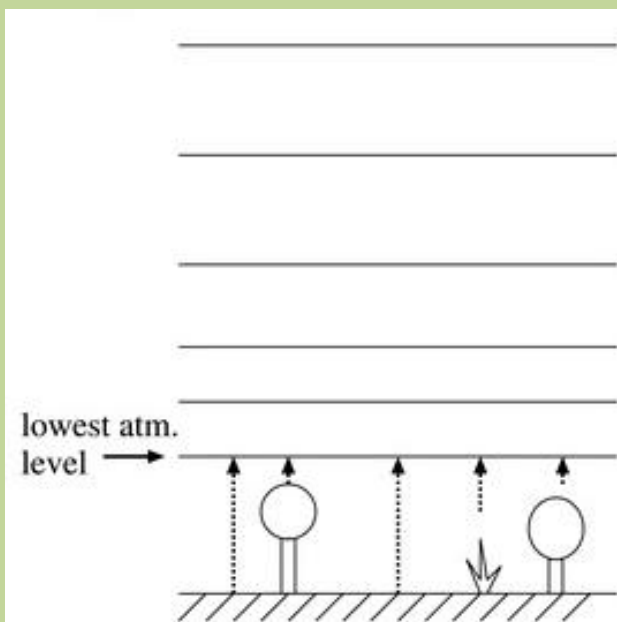
- As a preliminary step we validate the canopy model using data from the Canopy Horizontal Array Turbulence Study (CHATS)
 - We are not actually simulating a low-intensity fire here.
 - Goal: Reproduce the observed evolution of mean flow properties and the shape of the mean profiles (e.g., wind speed) in and above a vegetation layer

Model Overview

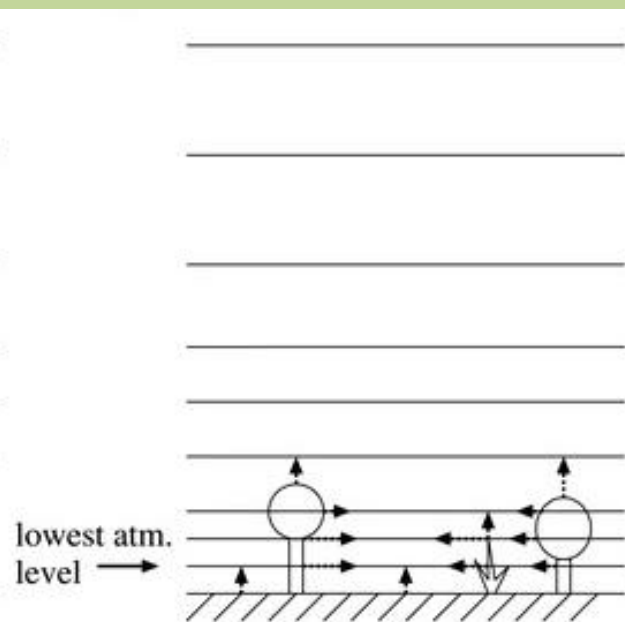
- Advanced Regional Prediction System (ARPS) Version 5.2.7 (Xue et al. 2003)
 - Three-dimensional atmospheric modeling system
 - Designed to simulate microscale [$O(10\text{ m})$] through regional scale [$O(10^6\text{ m})$] flows
- Standard ARPS lacks the capability to model atmospheric variables (e.g, wind, temperature) within a multi-layer canopy
- Standard ARPS accounts for the bulk effect of a vegetation canopy on the free atmosphere within single layer

Surface layer Modeling

Standard ARPS



Modified ARPS



LES Modeling

- ARPS is run in Large Eddy Simulation (LES) mode
 - The model resolves turbulence larger in scale than the grid spacing, and parameterizes smaller scales
- ARPS retains equations for: momentum, potential temperature, pressure, moisture, turbulent kinetic energy (TKE)
- ARPS parameterizes: radiation, sub-grid scale (SGS) turbulence, microphysics, surface processes

Modifications to ARPS code

- Canopy dynamic parameterization

- **Dupont and Brunet (2008,2009)**

- Momentum Equation: Pressure and Viscous Drag force

term: $-\eta\bar{\rho}C_d A_f \sqrt{\tilde{u}_j \tilde{u}_j} \tilde{u}_i$

- SGS TKE Equation: Wake energy sink (eddies larger than canopy elements lose TKE to wake scales and heat):

- **Kanda and Hino (1994)**

$-2\eta C_d A_f \sqrt{\tilde{u}_j \tilde{u}_j} e$

- SGS TKE Equation: Wake energy production (mean flow and resolved eddies interact with canopy elements):

η : Vegetation fraction

C_d : Canopy drag coeff.

A_f : Frontal area density

\tilde{u}_i : Instantaneous velocity component

α : wake production coefficient

e : subgrid-scale turbulent kinetic energy

$+ \eta \alpha C_d A_f \sqrt{\tilde{u}_j \tilde{u}_j}^3$

Modifications to ARPS code

- Canopy heat source parameterization
 - Yamada (1982), Sun et al. (2006)
 - Radiation Scheme: Net radiation at canopy top:

$$R_{Nh} = (1 - \alpha_t)S + \varepsilon_c \left(R_{Lh} \downarrow - \sigma T_c^4 \right)$$

- Radiation Scheme: Profile of net radiation inside canopy:

$$R_{Np}(z) = R_{Nh} \left[\exp\{-kL(z)\} - \eta \left(1 - \frac{z}{h} \right) \exp\{-kL(0)\} \right] \quad L(z) = \int_z^h A_f dz$$

α_t : Canopy albedo	R_{Nh} : Net radiation flux at canopy top	T_c : Canopy top temperature
S : Incoming solar rad.	$R_{Lh} \downarrow$: Longwave absorbed at canopy top	h : Canopy height
ε_c : Emissivity of trees	$L(z)$: Local leaf area index	k : Attenuation coefficient

Modifications to ARPS code

- Canopy heat source parameterization
 - Yamada (1982), Sun et al. (2006)
 - Thermodynamic Equation: Heat source inside canopy:

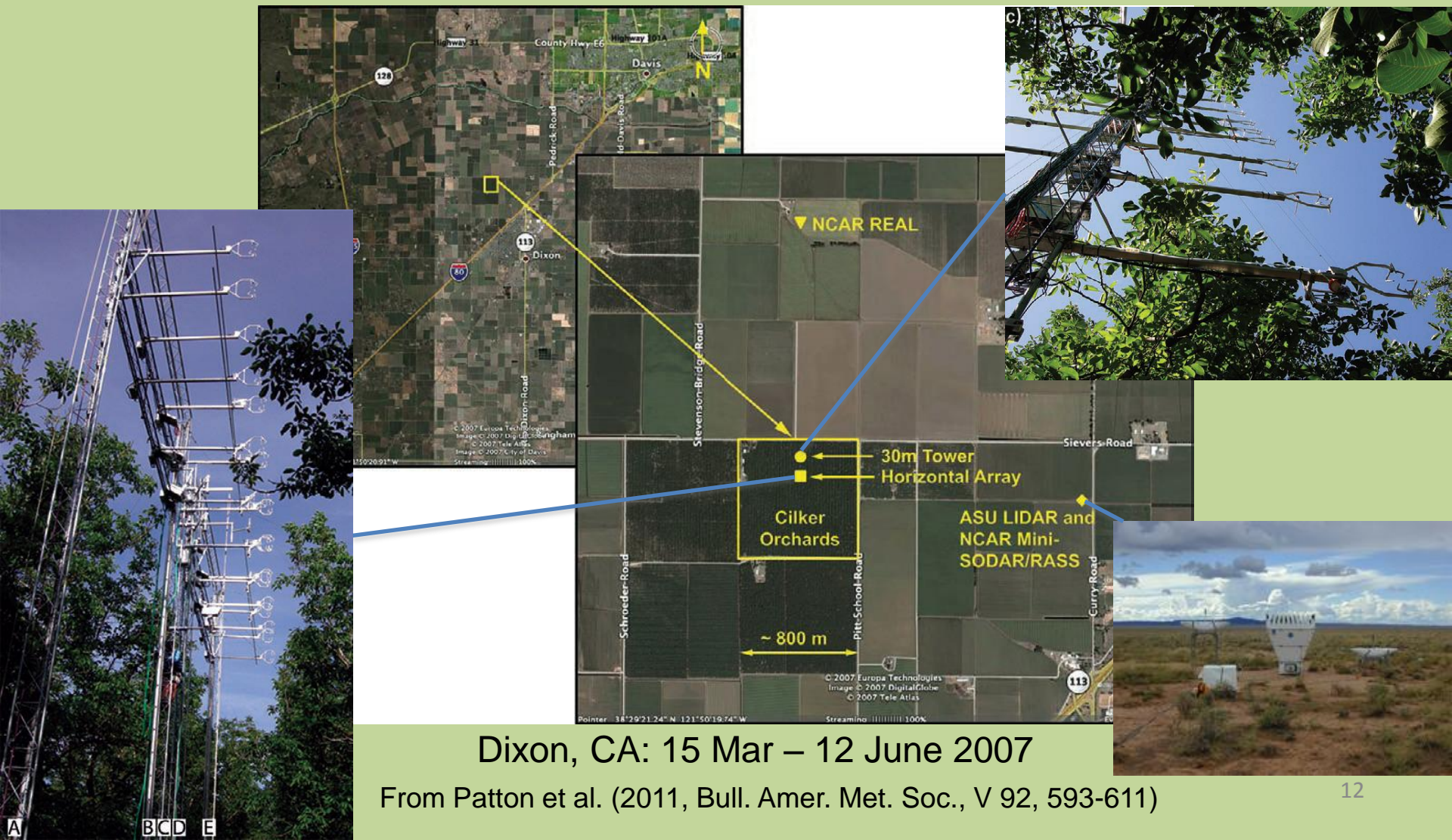
$$\frac{\partial \theta}{\partial t} = \underbrace{\frac{(1-\eta)}{\rho_a C_p} \frac{\partial R_N}{\partial z}}_{\text{Clearing fraction}} + \underbrace{\frac{\eta}{\rho_a C_p + \rho_c C_c} \left(1 + \frac{1}{B}\right)^{-1} \frac{\partial R_{Np}}{\partial z}}_{\text{Vegetated fraction}}$$

- Land Surface Model: Ground net radiation flux:

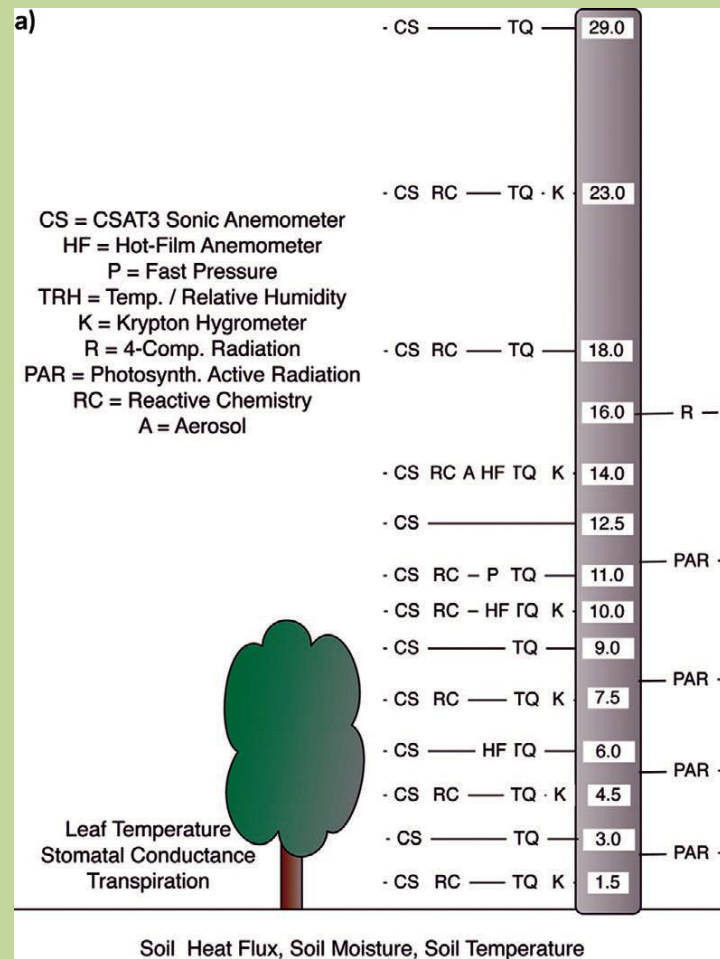
$$R_{NG} = \underbrace{\eta R_{Nh} \exp[-k L(0)]}_{\text{Vegetated fraction}} + \underbrace{(1-\eta) [(1-\alpha_G) S + \varepsilon_G (R_{LG} \downarrow - R_{LG} \uparrow)]}_{\text{Clearing fraction}}$$

θ : Potential temperature	C_p : Specific heat of air	
ρ_a : Air density	C_c : Specific heat of canopy	R_{NG} : Net radiation flux at ground
ρ_c : Canopy density	B : Bowen ratio	R_{LG} : Longwave radiation at ground

Canopy Horizontal Array Turbulence Study (CHATS)



30 m Tower



CHATS Summary

Pre leaf-out



Post leaf-out

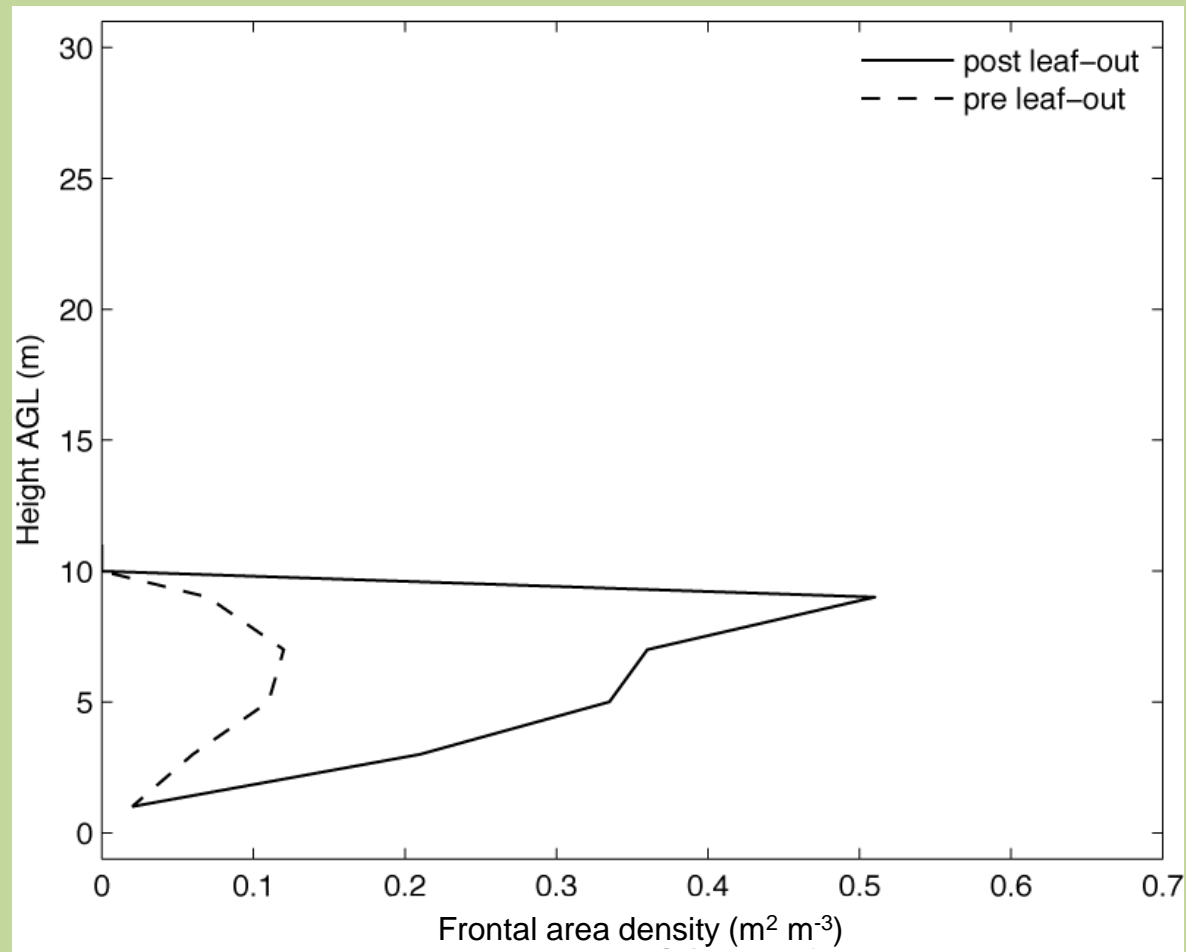


Model Strategy

- 3D simulations with 83 x 83 x 83 grid points
 - $\Delta x = \Delta y = 90$ m
 - $\Delta z = 2$ m up to $z = 84$ m AGL, vertically stretched above
- Initialized with single sounding; periodic BC applied
- Initialized at 1200 UTC (0500 LT), run for 12 hours
- Homogeneous canopy, uniform flat terrain
- Microphysical parameterization omitted
- Initial soil temperature & moisture derived from CHATS measurements
- Domain centered on tower (38.488 N; -121.846 W)

CHATS Cases: Vegetation Profiles

Averaged profiles measured by Li-Cor LAI-2000

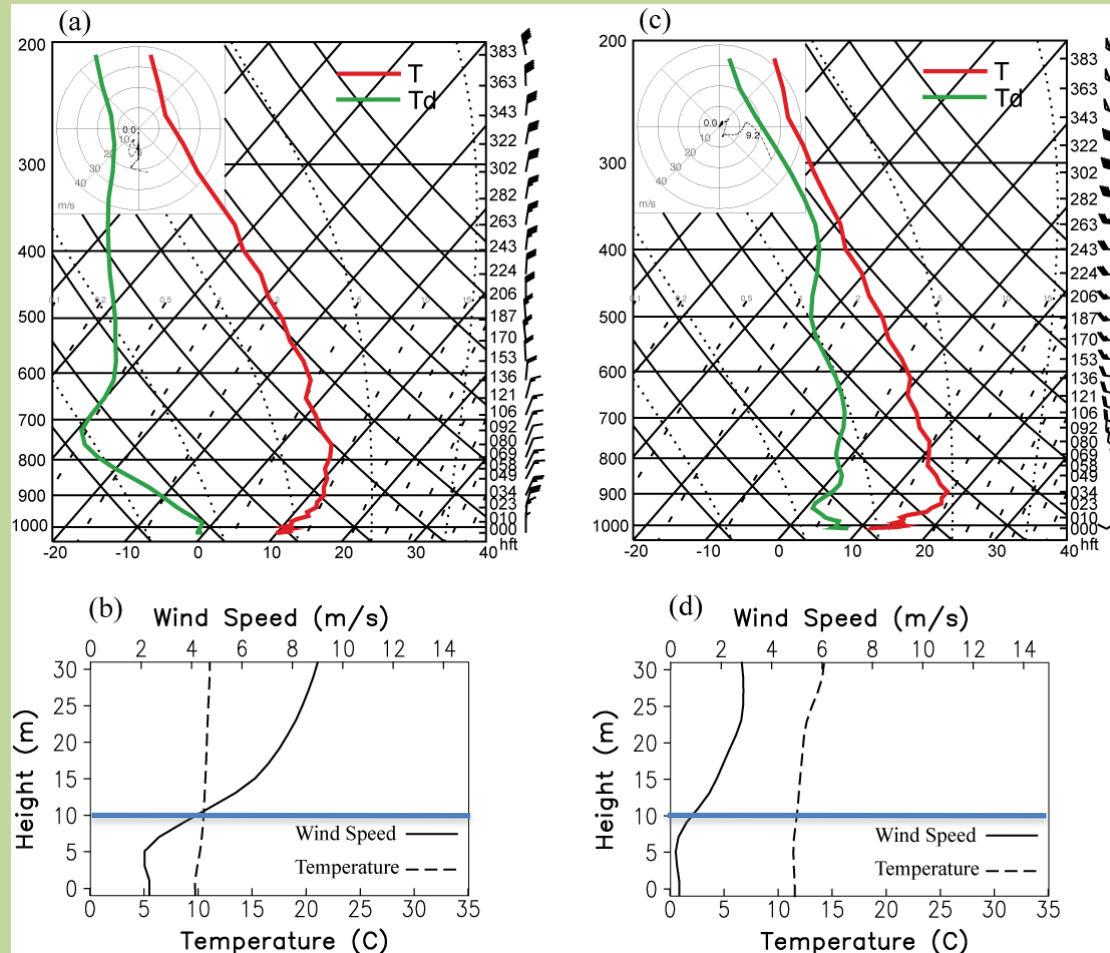


CHATS Cases: Meteorology

1200 UTC (0500 LT)

Pre leaf-out: 29 March 2007

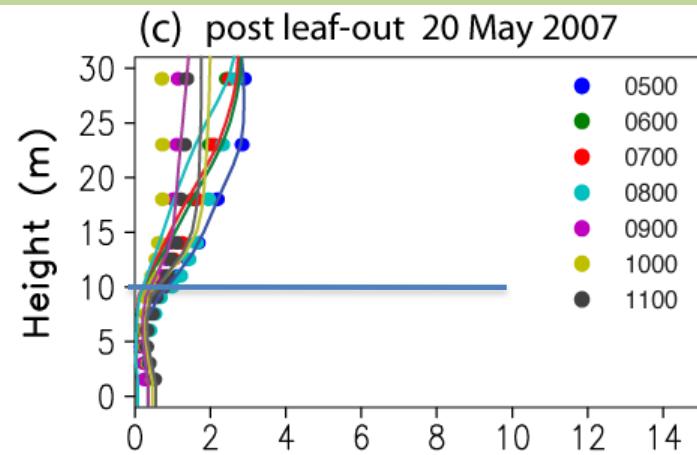
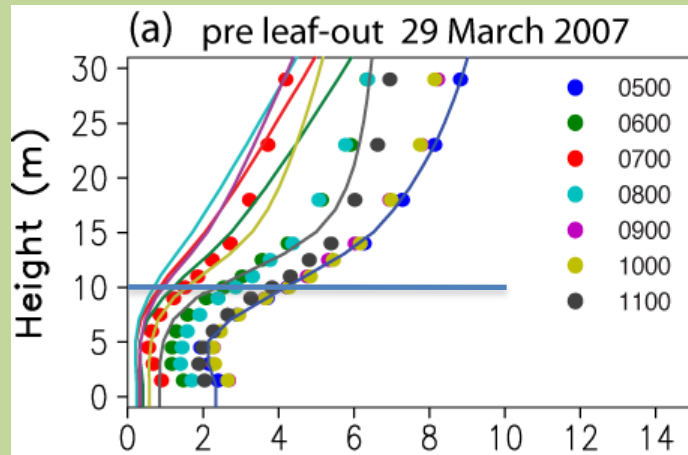
Post leaf-out: 20 May 2007



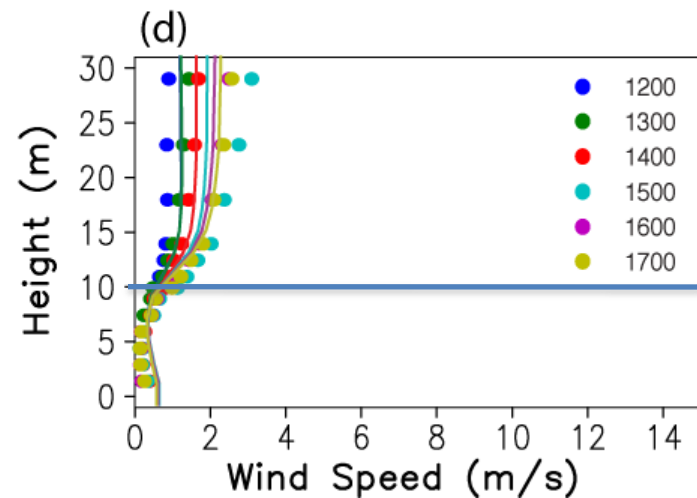
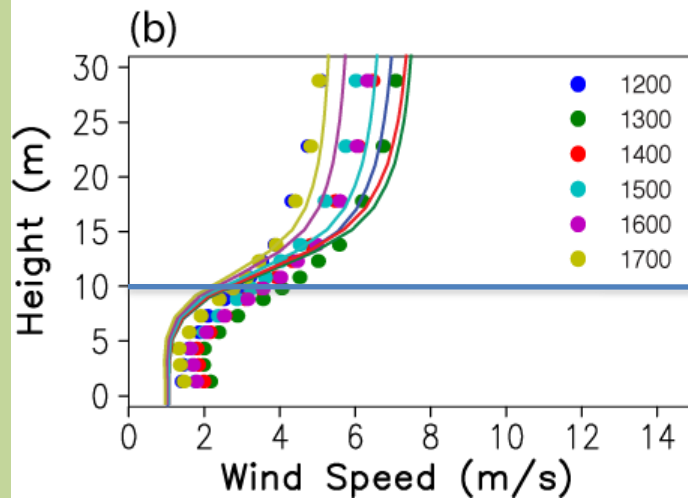
Model Validation

Mean Wind Speed

AM



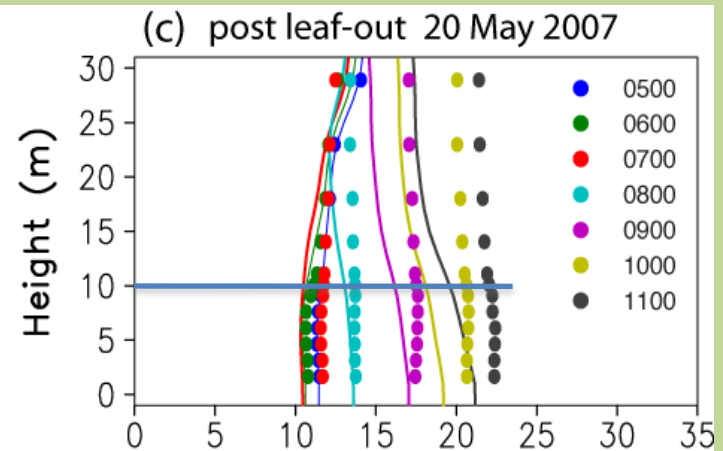
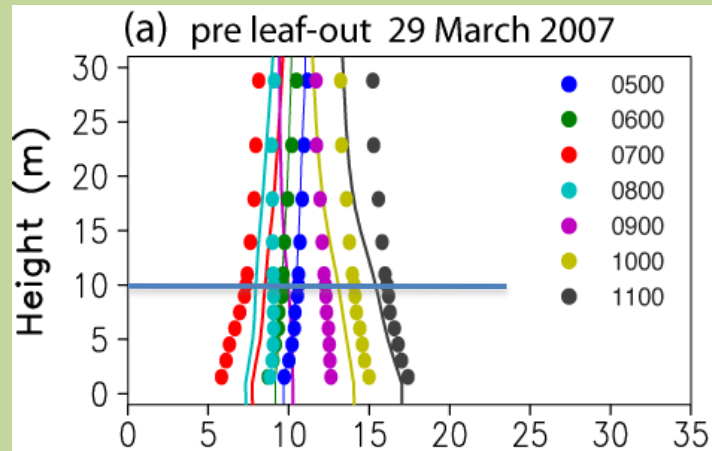
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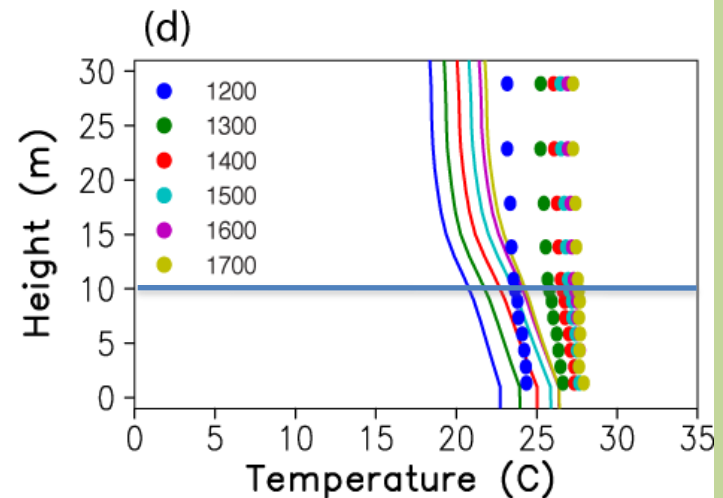
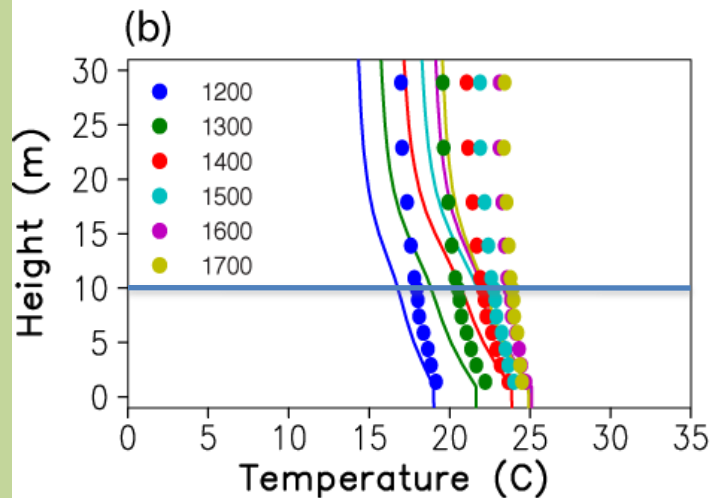
Model Validation

Mean Temperature

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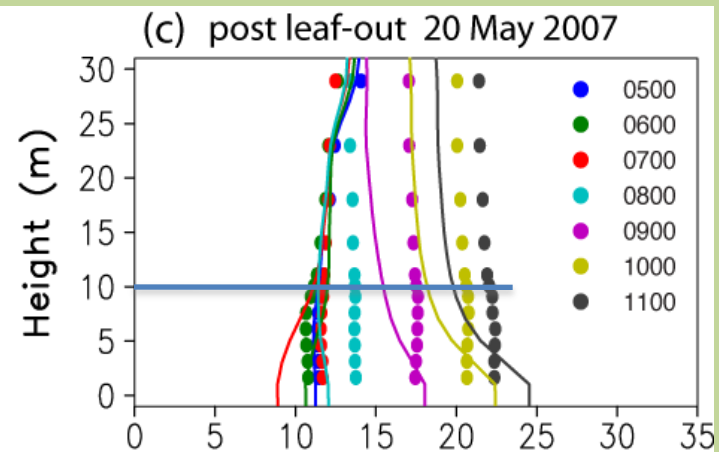
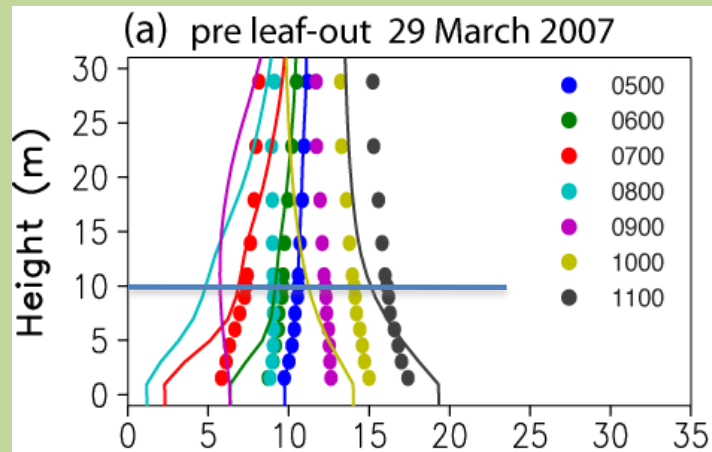
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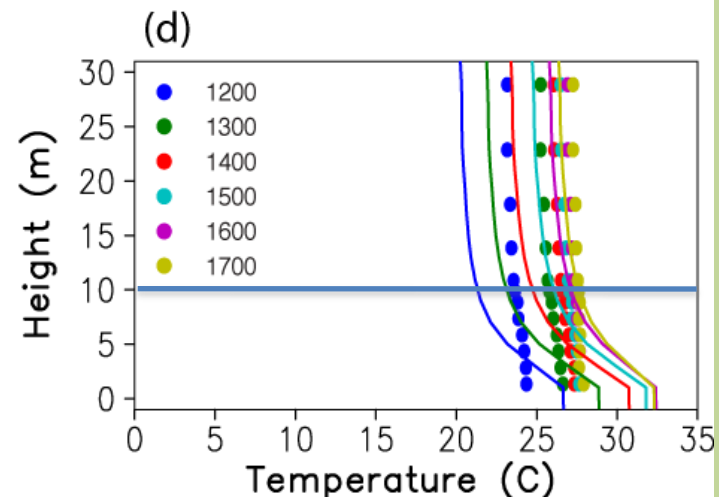
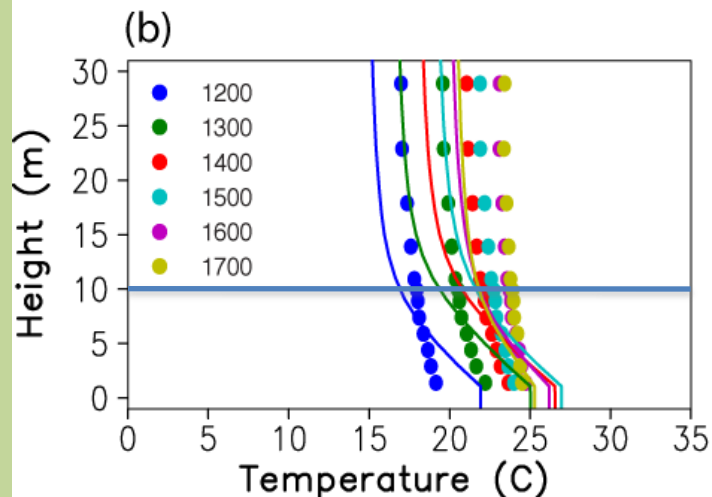
Sensitivity Experiments : No Canopy

Mean Temperature

AM



PM



Summary

- ARPS model code modified to allow modeling of flow through a multi-layer canopy
- Canopy modeling system validated against data from CHATS experiment
- Wind speed assessment very promising
- Temperature assessment reveals underlying model cool bias (independent of canopy modification)

Ongoing Efforts

- Apply CHATS validation findings to real-case simulations with low-intensity fires
- Pass meteorological fields to dispersion module
- Evaluate performance of models (ARPS,WRF) against data collected during March 2011 prescribed burn in NJ Pine Barrens

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- CHATS experiment team
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<http://www.geo.msu.edu/firesmoke/>

